

U.S. Express Mail No.: EL 560495228US  
Filing Date: September 10, 2003

PATENT  
Howrey Dkt. No. 04813.0045.CPUS03  
Metallic Power Ref. No.: MPPT.0040.CIPUS03

## **METHOD FOR OPERATING A METAL PARTICLE ELECTROLYZER**

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This application is a continuation-in-part of U.S. Patent Application Serial No. 10/424,539 filed April 24, 2003, which is hereby incorporated by reference herein as though set forth in full.

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This application claims the benefit of U.S. Provisional Application No. 60/410,561 filed September 12, 2002, U.S. Provisional Application No. 60/410,426 filed September 12, 2002, U.S. Provisional Application No. 60/410,548 filed September 12, 2002, U.S. Provisional Application No. 60/410,565 filed September 12, 2002, and U.S. Provisional Application No. 60/410,590 filed September 12, 2002, each of which is hereby fully incorporated by reference herein as though set forth in full.

## **BACKGROUND OF THE INVENTION**

### **1. Field of the Invention**

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This invention relates generally to production of metal particles through electrolysis, and more specifically, to a method for operating a metal particle electrolyzer to optimize electrolyzer service life and metal particle quality.

## 2. Related Art

There are many applications for metal particles produced through electrolysis including, for example, for use as feedstock for laboratory and industrial processes, and for use in refuelable and regenerative metal/air fuel cells. In these fuel cells, the metal particles function as the fuel for replenishing discharged fuel cells, and this fuel can be regenerated from the spent reaction solution which results from fuel cell discharge. In applications such as this, it is desirable to be able to regenerate the metal particles in a space efficient and self contained manner so that the regeneration of the metal particles can take place at the same location as the power source or cell stack within the fuel cell.

For additional information on metal/air fuel cells, the reader is referred to the following patents and patent applications, which disclose a particular embodiment of a metal/air fuel cell in which the metal is zinc: U.S. Patent Nos. 5,952,117; 6,153,328; and 6,162,555; and U.S. Patent Application Nos. 09/521,392; 09/573,438; and 09/627,742, each of which is incorporated herein by reference as though set forth in full. The term “fuel cell” as used throughout this disclosure is synonymous with the terms “battery” and “refuelable metal/air battery.”

Unfortunately, known methods of producing metal through electrolysis are all unsatisfactory for these applications. Some methods, e.g., electroplating, do not produce metal in the required particulate form, and require expensive and cumbersome mechanical processing to put the metal in the required form.

For example, a method disclosed in U.S. Patent No. 4,164,453 forms zinc dendrites on cathode tips that protrude into an anodic pipe carrying a flow of zincate solution. The cathode protrusions are specially formed in a curved configuration. Dendrites form on the cathode tips during low flow in one direction, and are then dislodged during high flow in the opposite direction. This technique is not suitable for

particle production because it yields dendritic zinc that requires further processing to make pellets. Also, the curved cathodic protrusions are expensive to manufacture, and spatially inefficient.

Another method, represented by U.S. Patent No. 5,792,328, involves electro-  
5 depositing dendritic or mossy zinc onto the surface of a planar cathode plate, and then scraping the zinc from the surface of the cathode. Since the recovered metal is in the form of mossy dendrites, and cannot be easily put into the desired particulate form absent expensive and complicated mechanical processing steps, this method is likewise not suitable.

10 A third method, in U.S. Patent No. 3,860,509, uses a cathodic surface that consists of many small conductive areas in the hundred micron range spaced apart by an insulating matrix. These areas are exposed to a high temperature metal bearing electrolyte solution which, by electrolysis, deposits metal dendrites on the cathode. The metal is recovered by mechanically scraping the cathode which produces a powdery metal dust composed of  
15 particles so small that they are not suitable for use in a metal/air fuel cell.

A fourth method, known as electrowinning, represented by U.S. Patent Nos. 5,695,629 and 5,958,210, involves immersing seed particles in an electrolyte, and causing metal to form over the seed particles through electrolysis. However, because of the risk that metal particles will get caught in a porous separator between the anode and cathode,  
20 and cause a disastrous short between the anode and cathode, this method is unsatisfactory. Another factor weighing against this method is the burden and expense of maintaining a supply of seed particles.

Another method, represented by U.S. Patent No. 5,578,183, involves forming dendritic or mossy metal on a cathode through electrolysis, removing the metal, and then

pressing the metal into pellets through mechanical forming steps such as extrusion. This technique is unsuitable for the applications mentioned earlier because the required mechanical forming steps are expensive, and do not permit a space-efficient and self-contained particle recovery process.

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### SUMMARY

A method for operating a metal particle electrolyzer is described. The method extends the service life of the electrolyzer, and controls the quality of metal particles produced by the electrolyzer by maintaining current density through the electrolyzer cathode within a preferred range. An operating range for cell voltage across the anode and cathode of the electrolyzer is determined based on cathode configuration. A particle growth cycle is initiated by a power supply energizing the electrolyzer immersed in an electrolyte solution containing dissolved metal. Cell voltage is monitored and power supply output is adjusted responsive to the monitored voltage to maintain the current density in the preferred range. In one embodiment, current density is maintained in a range between about 10,000 A/m<sup>2</sup> and 40,000 A/m<sup>2</sup>. In another embodiment, power supply output is adjusted to maintain cell voltage within 20% of an optimal value. In another embodiment, the electrolyte solution is a reaction product of an electrochemical reaction in a metal/air fuel cell in which the metal may be zinc.

After particles are grown to a desired size, the particles are removed from the cathode, and cell voltage polarity is reversed to dissolve particles embedded in the cathode surface. Reverse polarity voltage is maintained at a value sufficiently low to preclude oxygen evolution on the electrode surface that was formerly the cathode. After a period of time has elapsed to allow for dissolving of embedded particles, the growth cycle is completed, and another cycle may begin. During application of reverse polarity voltage, peak current through the electrolyzer may be monitored to indicate a cathode

surface condition. When peak current exceeds an operating limit, the electrolyzer may be de-energized, and the cathode surface may be mechanically reconditioned to extend the service life of the electrolyzer.

5 A means for electrolyzing the dissolved metal using a discrete particle electrolyzer is also described. An anode and cathode spaced from one another are at least partially immersed in a solution of dissolved metal. The surface of the cathode is configured with one or more active zones separated from one another by an insulator. The active zones are made of a material which is electrically conductive. An electric potential is applied between the anode and the cathode while the solution containing the dissolved metal is  
10 caused to flow along the surface of the cathode. The electric potential causes an electric current to flow through the solution. The current density is sufficient to allow metal particles to form on the active zones of the cathode through electrolysis. When the metal particles are of sufficient size, they are removed from the surface of the cathode through a scraper or other suitable means integral to the cathode structure, and applied to the  
15 surface of the cathode.

Other systems, methods, features and advantages of the invention will be or will become apparent to one with skill in the art upon examination of the following figures and detailed description. It is intended that all such additional systems, methods, features and advantages be included within this description, be within the scope of the invention,  
20 and be protected by the accompanying claims.

### **BRIEF DESCRIPTION OF THE FIGURES**

The invention can be better understood with reference to the following figures. The components in the figures are not necessarily to scale, emphasis instead being placed

upon illustrating the principles of the invention. Moreover, in the figures, like reference numerals designate corresponding parts throughout the different views.

Figure 1 illustrates a first embodiment of a system for producing metal particles through electrolysis, including a lateral view of electrolyte flow across the cathode surface.

Figure 2a shows the front view of an embodiment of a cathode.

Figure 2b shows a magnified side view of the cathode of Figure 2a.

Figure 3a shows a side view of a second embodiment of a cathode.

Figure 3b shows a top view of the cathode of Figure 3a.

Figure 4 illustrates an embodiment of a system for producing metal particles through electrolysis in which a cylindrical cathode is mounted within an anode pipe.

Figure 5 illustrates an embodiment of a system for producing metal particles through electrolysis configured with a double-sided planar cathode.

Figure 6 illustrates an embodiment of a system for producing metal particles through electrolysis configured with multiple double-sided planar cathodes in a series configuration and dielectric material separating adjacent anodes.

Figure 7 illustrates an embodiment of a system for producing metal particles through electrolysis configured with multiple dual cathodic/anodic plates in a series configuration.

Figure 8 shows an embodiment of a system for producing metal particles through electrolysis in which particle removal is achieved through movement of a moveable planar cathode past a stationary scraper.

5 Figure 9 is a partial view of an embodiment of a system for producing metal particles through electrolysis in which particle removal is achieved through rotation of a cylindrical cathode past a stationary scraper.

Figure 10 is an exploded view of a system for producing metal particles through electrolysis in which particle removal from a planar cathode is achieved by means of a rotary scraper.

10 Figure 11 illustrates an embodiment of a system for producing metal particles through electrolysis configured with means for collecting particles and automatically refueling a fuel cell with the collected particles.

Figure 12 illustrates an apparatus for conducting simulations of systems for producing zinc particles.

15 Figure 13 plots regions of zinc particle quality as a function of current density and ZnO molarity, based on simulations conducted using the experimental testing apparatus of Figure 12.

Figure 14a shows a magnified cross sectional view of metal particle formation on a cathode surface according to one embodiment of the invention.

20 Figure 14b shows a magnified view of the first phase of metal particle formation on an active zone of a cathode according to one embodiment of the invention.

Figure 14c shows a magnified view of the second phase of metal particle formation on an active zone of a cathode according to one embodiment of the invention.

Figure 15a shows a sliced planar cross section of a cathode surface formed from an insulated bundle of wire according to one embodiment of the invention.

5        Figure 15b shows a side view of a fixture for spacing an insulated bundle of wire for manufacturing cathodes.

Figure 16a shows a top view of a metal plate machined to form active zones in hexagonal array to form a planar cathode surface according to one embodiment of the invention.

10        Figure 16b shows a side view of the plate of Figure 16a.

Figure 16c shows a magnified side view of the plate of Figure 16a.

Figure 16d shows a magnified side view of the plate of Figure 16a after the addition of a layer of insulating material to the surface of the plate.

15        Figure 16e shows a magnified side view of the plate of Figure 16d after finishing the surface.

Figure 17a illustrates a minimal number of active zones arranged in a hexagonal array.

Figure 17b shows a plurality of active zones arranged in a hexagonal array.



Figure 17c depicts active zones in hexagonal array on coins of different shapes that form a portion of a planar cathode surface formed according to one embodiment of the invention.

Figure 17d shows a top view of a metal strip for preparing coins shown in Figure  
5 17c.

Figure 17e shows a magnified side view of the metal strip of Figure 17d after coatings have been applied to its top and bottom surfaces.

Figure 17f illustrates the metal strip of Figure 17d punched to form hexagonal coins of Figure 17c.

10 Figure 17g depicts a hexagonal coin having a plurality of active zones stamped on its surface.

Figure 17h illustrates a portion of a planar cathode surface configured from a plurality of hexagonal coins of Figure 17g.

Figure 18a shows a top view of an metal plate etched to define active zones that  
15 form a planar cathode surface according to one embodiment of the invention.

Figure 18b shows a magnified side view of the plate of Figure 18a after adding a layer of insulating material to the etched surface.

Figure 18c shows magnified views of an active zone comprising multiple layers of metal formed according to one embodiment of the invention.

20 Figure 19 is a flow chart of a method according to one embodiment of the invention of manufacturing a cathode by chemically etching a metal substrate.

Figure 20 illustrates an embodiment of a method according to the invention for producing metal particles.

Figure 21a illustrates an embodiment of a method according to the invention for removing particles from a cathode.

5        Figure 21b illustrates a second embodiment of a method according to the invention for removing particles from a cathode.

Figure 22a shows a magnified cross-sectional view of an electrolyzer having irregular areas on the active zones of a cathode.

10       Figure 22b shows a magnified cross-sectional view of the cathode of Fig. 22a after reconditioning.

Figure 23 illustrates an embodiment of a method according to the invention for operating an electrolyzer.

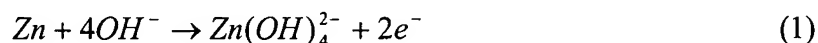
Figure 24 illustrates another embodiment of a method according to the invention for operating an electrolyzer using reverse-polarity cleansing.

15       Figure 25 illustrates another embodiment of a method for operating an electrolyzer using reverse-polarity cleansing and mechanical reconditioning.

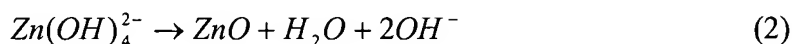
### **DETAILED DESCRIPTION**

20       Figure 1 illustrates a system 100 configured to produce metal particles by electrolysis of a reaction solution 110 that contains dissolved metal. Solution 110 may be aqueous or non-aqueous, and may be an electrolyte, acid, or organic solvent. It may contain metal ions in the form of one or more oxides or salts of the metal. In one implementation,

the solution 110 contains reaction products, such as zincate, of an electrochemical reaction occurring in a metal/air fuel cell. Examples of the metal include zinc, copper, nickel, and potassium. In one implementation example, the reaction solution comprises potassium hydroxide (KOH) containing zincate,  $Zn(OH)_4^{2-}$ , or dissolved zinc oxide, ZnO, a white  
5 non-toxic powder which is soluble in the reaction solution. The zincate in this implementation example may be produced through the following electrochemical reaction which occurs in one embodiment of a zinc/air fuel cell:

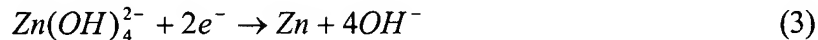


Zinc oxide may then be formed through precipitation of the zincate in accordance with  
10 the following reaction:



The system 100 produces metal particles through electrolysis which occurs between the rightmost surface of anode 104 and the leftmost surface of cathode 106. Anode 104 and cathode 106 are electrodes at least partially immersed in solution 110, and  
15 are coupled, respectively, to the positive and negative terminals of power supply 112. The solution 110 is contained within container 114.

In the previously discussed implementation example of system 100, the following reaction may take place at the cathode:



20 The two electrons in this equation originate from the cathode where the following reaction takes place:



Pump 108 provides a means for circulating solution 110 into and out of container 114. The solution flows into container 114 through conduit 116, and flows out of container 114 through conduit 118. By pumping solution into and out of container 114, a flow path 120 of solution along the surface of cathode 106 is created. Cathode 106 includes on its surface a plurality of active zones 102 that are exposed to the solution 110 flowing along flow path 120. As pump 108 causes solution 110 to flow past the active zones 102, while power supply 112 energizes anode 104 and cathode 106, metal particles are formed on the active zones 102 by electrolysis. Once formed, the particles may be removed from the active zones 102 by a scraper or other suitable means. The active zones 102 may be formed of a material with easy release surface properties to facilitate removal of the metal particles. These surface properties may be imbued by a suitable coating added to the surface of the active zones, or through oxidation of the surface of the active zones. Materials capable of forming active zones having oxide layers include magnesium, nickel, chromium, niobium, tungsten, titanium, zirconium, vanadium, and molybdenum.

The active zones 102 are formed of a conductive material and are electrically coupled to conductor 122 within the cathode 106. The active zones 102 are electrically isolated from one another at the cathode surface by an insulator. The design of the conductor, insulator, and active zones may be tailored to suit a particular application, thus, the surface of the cathode may take on a variety of forms. It may be flat or curved, and have a general shape that is planar, cylindrical, spherical, or any combination thereof. The cathode may have a single surface with active zones, or may have multiple surfaces with active zones. The size and number of the active zones on the surface of the cathode determine, generally, the size and number of metal particles that the system will produce in a single operation.

An active zone, considered separately, may itself have a flat or curved surface, may assume any regular geometric shape, or may have an irregular shape. The separation distance between the nearest points of any two active zones is between about 0.1 mm and about 10 mm, preferably between about 0.4 mm and about 0.8 mm, and the surface area of each active zone is no less than about 0.02 square mm. The active zones, considered collectively, may comprise multiple shapes, sizes and placement patterns. The active zones may be formed from the conductor, or may be separate parts connected thereto.

A perforated insulator that covers the conductor, exposing areas of the conductor to the cathode surface, may form the active zones. It is also possible to form the insulator by creating an oxide layer on the surface of the conductor that separates the active zones. A skilled artisan will appreciate from a reading of this disclosure that the conductor, insulator, and active zones may be composed from a variety of materials, and be configured in a variety of ways. Accordingly, many variations in the design of the cathode are possible.

One embodiment of a cathode 200 is illustrated in Figure 2a. In this embodiment, cathode 200 has a generally planar form, with a plurality of active zones 202 occupying one of the planar surfaces 212. A plurality of pins 204 extend from and are electrically coupled to conductor 206 within the cathode 200, as shown in magnified form in Figure 2b. The ends of the rods 204 at the surface 212 of the cathode form the active zones 202. The rods 204 may be machined from conductor 210, or may be separately attached to conductor 210 by threaded connection, welding, or other means. Both the rods 204 and conductor 210 are electrically conductive, but need not be made from the same material. An insulator 208 fills the gaps between rods 204 to maintain separation and electrical isolation between the active zones 202 and create a generally flat surface 212. It also coats the remaining surfaces of conductor 210 sufficiently such that the active zones 202

are the only conductive portion of cathode 200 which is immersed in solution 110 in the system 100. The insulator 208 may be formed from a potting compound, a molded plastic, or any other dielectric material.

A second embodiment of a cathode 300 is illustrated in Figures 3a. In this  
5 embodiment, cathode 300 is generally cylindrical in form, with a plurality of active zones 302 spaced around the outer surface 312 of the cylinder. As illustrated in Figure 3b, rods 304 extend radially outward from conductor 306, and the ends thereof at the outer surface 312 of the cylinder form the active zones 302. Conductor 306 includes a center terminal 310 that extends axially through the cylinder, and acts as a means for external electrical  
10 connection. Insulator 308 fills the interstices between active zones 302 to achieve electrical isolation of the active zones from at each other at surface 312, and also to complete the surface 312.

Figure 4 illustrates a second embodiment of system for metal particle production. In system 400, the electrolysis occurs inside a metal pipe 404 that functions as the anode.  
15 Metal pipe 404 has a first portion 414 and a second portion 416, and cathode 406 is situated within the second portion 416 of the pipe 404 as shown. Solution 410 flows through pipe 404, entering the first portion 414 and exiting the second portion 416 as shown. At the same time, power supply 412 creates an electric potential between pipe 404 and cathode 406. In one embodiment, the cathode 406 is cylindrical in shape and is  
20 configured as shown in Figure 3a. The active zones of cathode 406 are identified with numeral 402. A bus bar 408 couples electrical energy from power supply 412 to the cathode 406 through a penetration 418 in pipe 404, while maintaining a watertight seal for pipe 404 at the point of penetration 418, and maintaining electrical insulation between cathode 406 and pipe 404 at the point of penetration 418.

A third embodiment of a system 500 for metal particle production is illustrated in Figure 5. In system 500, a double-sided planar cathode 506 is situated between planar anodes 504a and 504b. In a manner similar to system 100 illustrated in Figure 1, pump 508 circulates solution 510 into container 514 through conduit 518, and out of container 514 through conduit 520. The solution 510 is caused to flow past the surfaces 506a and 506b of cathode 506 by means respectively of flow paths 516a and 516b. Flow paths 516a and 516b in turn are created through the circulation of the solution 510 through the container 514. While solution 510 flows along flow paths 516a and 516b, power supply 512 energizes anodes 504 and cathode 506 to cause formation of metal particles on active zones 502 of the surfaces 506a and 506b of cathode 506. Once formed, the metal particles may be removed as in the previous embodiments. In this embodiment, anodes 504 are electrically connected in parallel.

A fourth embodiment of a system 600 for metal particle production is illustrated in Figure 6. System 600 comprises a plurality of the systems of Figure 5 coupled in series. In Figure 6, four such systems are shown, identified with numerals 624a, 624b, 624c, and 624d, but it should be appreciated that embodiments are possible in which fewer or more than four such systems are provided.

The series connection is achieved as follows: Coupler 616 connects the positive terminal of power supply 602 to the anode pair in the first system 624a. Coupler 618 connects the cathode in the first system 624a to the anode pair in the second system 624b. Similar couplers respectively connect the cathode in the second system 624b to the anode pair in the third system 624c, and the cathode in the third system to the anode pair in the fourth system 624d. The cathode in the fourth system 624d is then coupled to the negative terminal of power supply 602 through coupler 620. A dielectric material 622

may be placed between the anode plates in adjacent systems that may be at different electric potentials to prevent electrolysis between anodes.

A pump 626 pumps solution to each of the system 624a, 624b, 624c, and 624d through conduit 628 in the manner shown. The solution flows through each of the systems 624a, 624b, 624c, and 624d, through flow paths which cause solution to flow across the two surfaces of the cathode in each system. After flowing through the individual system, the solution then collects in the bottom 632 of the overall system 600, and is then returned to pump 626 by means of conduit 630. Each of the systems 624a, 624b, 624c, and 624d are configured as previously described in relation to the system of Figure 5.

Figure 7 illustrates a fifth embodiment of a system 700 for producing metal particles. In system 700, each of electrodes 706 is a bipolar cathodic-anodic plate, having an anode plate on one surface, and having on the other surface a plurality of active zones electrically coupled to the anode plate and separated from each other by an insulator. The series connection is made by coupling the positive terminal of power supply 702 to electrode 704, which is a plain anode plate, and by coupling the negative terminal of 702 to electrode 708, which is a plain cathode plate. This creates a path for the flow of electric current from anode 704 through the sequence of bipolar electrodes 706 to cathode 708. Thus, a series configuration of bipolar electrodes 706 is formed in which the dielectric material and coupling devices included in the system of Figure 6 are eliminated.

Pump 712 pumps solution through conduit 714 into the system 700 such that individual flow paths are created to cause the solution to flow past the cathode 708, and the cathodes in each of the electrodes 706. The solution is then returned to pump 712 by means of conduit 716.



Various means are possible form removing particles from the active zones of the cathode when they have reached the desired size. For example, particles may be removed by scraping the cathode surface, by vibrating the cathode, by delivering a mechanical shock to the cathode, or by increasing the flow velocity of the solution. One embodiment of a scraping means is illustrated in Figure 8. In this embodiment, cathode 806 has outward facing active zones 802 and is movable relative to stationary scraper 804. After particles have accumulated on the active zones 802, cathode 806 is moved from position A to position B (or vice versa) such that the outer surface thereof passes against scraper 804, thus dislodging the particles. Scraper 804 may be composed of any material of a hardness sufficient to dislodge the metal particles from the active zones. In addition, as previously discussed, the material making up the active zones may have easy release surface properties to facilitate removal of the particles.

A second embodiment of a particle-removal system 900 is illustrated in Figure 9, which shows a cut-away view of a cylindrical anode 908 enclosing cylindrical cathode 906. A scraper 904 is situated against the active zones 902 on the surface of cathode 906. Cathode 906 is configured so that it can be moved relative to scraper 904. Cathode 906 is then rotated, causing particles to be scraped from active zones 902. Scraper 902 may be mounted directly to anode 908, or may be independently mounted.

Figure 10 shows an exploded view of a system according to one embodiment of the invention comprising a planar anode plate 1002 and cathode plate 1014 configured with a rotary scraper 1012. Anode plate 1002 is mounted to a back plate 1004 that provides a mounting location for drive motor 1006. Back plate 1004 also provides a fluid manifold 1008 for the passage of electrolyte solution. Drive motor 1006 is mechanically coupled to a scraper driver 1010 that is centrally located in anode plate 1002, as shown.

A scraper 1012 is coupled to scraper driver 1010 such that the scraper contacts, or nearly

contacts, the surface of cathode plate 1014. Cathode plate 1014, configured with a plurality of active zones, mounts to anode plate 1002 and back plate 1004 to complete the assembly and form a narrow channel (not shown) to conduct solution from fluid manifold 1008 down through the channel between anode plate 1002 and cathode plate 1014.

5           System 1000 operates generally as previously discussed to form metal particles on the surface of the active zones of cathode plate 1014. When the particles have grown to a desired size, drive motor 1006 is energized to rotate scraper 1012 against the particles with a minimal force required to dislodge the particles. In one embodiment, scraper 1012 may be rotated through one or more complete revolutions, as required to dislodge  
10 particles. In another embodiment, scraper 1012 may be rotated through one half of a complete revolution, thereby dislodging about half of the particles, then reversed and rotated in the opposite direction through a complete revolution to dislodge the remaining particles.

          In another embodiment, scraper 1012 may be oscillated like an inverted pendulum  
15 with an increasing amplitude. Initially, scraper 1012 is positioned vertically in a twelve o'clock position. Scraper 1012 then rotates through an initial angle comprising a partial revolution, then rotates in the opposite direction through an angle greater than the initial angle to dislodge more particles, then reverses direction again. As particles are dislodged, they fall from the cathode plate 1014 by means of gravity or entrainment in fluid flow.  
20 With each reversal, scraper 1012 is rotated through an angle greater than the previous one in order to cover unscraped areas of the cathode. This process is continued until the entire cathode surface is sufficiently scraped. In another embodiment, the initial position of scraper 1012 is at a position other than twelve o'clock, for example, six o'clock. At the six o'clock position, scraper 1012 oscillates as described above, causing any  
25 dislodged particles that accumulate on scraper 1012 to fall from the cathode plate 1014

with each reversal of direction. The advantage to the pendulum movement is that it prevents excessive accumulation of dislodged particles on the scraper, thereby allowing the drive motor to deliver a minimal force and reduce the risk of particle disintegration.

Figure 11 illustrates the system of Figure 5 equipped with a particle-collection means. When particles have reached the appropriate size, a scraper or other means (not shown) dislodges the particles. The dislodged particles then fall by gravity, through the flow of solution, or by some other suitable means into hopper 1104, where they are funneled into collection tube 1106 and entrained in fluid flow. Pump 1108 then draws the fluid borne particles through conduit 1110 for transport to a storage device or to a fuel cell for a metal/air battery.

In order to ensure consistent shape and quality of the metal particles, it may be necessary to maintain several operational parameters within certain ranges. The flow rate and temperature of the solution, the molarity of the dissolved metal, the electrolyte concentration, the Reynolds number of the flow path past the cathode surface, flow turbulence, the electric current through the solution, and the current density at the active zones are all parameters that may need to be controlled in order to produce good quality, crystalline particles that are free of dendritic formations. The Reynolds number  $Re$  is defined as follows:

$$Re = \frac{\rho U D_h}{\mu} \quad (5)$$

where  $\rho$  is the solution density,  $U$  is the solution velocity,  $\mu$  is the solution viscosity, and  $D_h$  is a length dimension defined as

$$D_h = 4 \left( \frac{WG}{2(W + G)} \right) \quad (6)$$

For a substantially rectangular flow channel, such as that depicted in Figure 1 for flow path 120, G is the gap between the anode and cathode plates. W is the width of the channel across the anode or cathode surface, measured as shown in Figure 2. In other words, W and G are the cross-sectional rectangular dimensions of the flow channel normal to the direction of flow. Thus, for a given  $\rho$ ,  $\mu$ , and  $D_h$ , the Reynolds number may be controlled by controlling the velocity of the solution flow. Generally, in particle-free fluid flow, Re greater than about 2000 promotes turbulent flow.

An apparatus for determining appropriate ranges for these parameters for a zinc particle production system configured to produce zinc particles through electrolysis of a potassium hydroxide solution containing zincate is illustrated in Figure 12. The configuration and operation of the apparatus is generally similar to that of Figure 1. Cathode 1206 in this apparatus comprises a 100 mm square Mg plate ( $W = 100$  mm) with 4900 circular active zones, each about 0.4 mm in diameter, evenly spaced in a square array. The cathode is formed from magnesium because this metal avoids a strong bond with electro-deposited zinc. The insulation separating the active zones on the cathode is formed from commercial epoxy adhesive. Cathode 1206 is partially submerged in the potassium hydroxide solution containing zincate and spaced 3 mm ( $G = 3$  mm) from anodic surface 1202. The anodic surface 1202 consists of a nickel mesh coated with oxygen evolution catalysts attached to the surface of a stainless steel plate 1204. Both cathode 1206 and anode 1202 are electrically connected to a constant current DC power supply 1212. The current from power supply 1212 can be varied from 0 to 300 A. Electrolyte 1210, consisting of aqueous solution of 45% KOH with different concentrations of ZnO, was pumped into and out of container 1214 (and through a flow

path between the spacing between cathode 1206 and anode 1202) by a 100 W centrifugal pump 1208. Preferably, electrolyte concentration should be kept within the 25 to 55 weight percent range. Electrolyte temperature was maintained between a preferred range of 40 and 55 degrees Centigrade, although satisfactory results may be achieved over a much wider temperature range of between 0 and about 100 C. Reynolds numbers were calculated according to equations (5) and (6) under different flow conditions. Using the apparatus described above, various flow rates, molarities and current densities were tested for their impact on particle consistency and quality.

The results of these tests are summarized in the graph of Figure 13. The graph plots regions of zinc particle quality as a function of current density and ZnO molarity, with the Reynolds number of the flow kept constant at approximately 3200, well within the turbulent flow range. Current density is calculated as the total load current divided by the sum of the active zone surface areas. Good quality crystalline particles were produced while operating the apparatus with ZnO concentrations in the preferred range of about 0.1 M < [ZnO] < about 4.5 M, and current densities in the preferred range of about 5,000 A/m<sup>2</sup> < I < about 40,000 A/m<sup>2</sup>. Current densities below about 10,000 A/m<sup>2</sup> produced poor quality zinc. At very high current densities, I > about 55,000 A/m<sup>2</sup>, the apparatus produced crystalline zinc too brittle to maintain particle integrity. Current densities I > about 30,000 A/m<sup>2</sup> with low zincate concentrations, i.e., [ZnO] < 0.4 M, also produced poor quality brittle, crystalline particles. Dendritic formations occurred only at very low concentrations, [ZnO] < about 0.2 M, and very high current densities I > about 15,000 A/m<sup>2</sup>. Also, under laminar flow conditions, where the Reynolds number, Re, was low, i.e., Re < about 1500, the system yielded zinc formations that were dendritic and amorphous, regardless of molarity and current density. These tests indicate that within the preferred ranges of temperature, molarity, and current density, maintaining a velocity

of the solution sufficient to promote turbulent flow. For purposes of this disclosure, terms such as “about” or “approximately” or “substantially” or “near” are intended to allow some leeway in numeral exactness which is acceptable in the trade. Generally speaking, these terms refer to variations of  $\pm 25\%$  or less. Also, for purposes of this disclosure, “turbulent” means sufficient agitation or fluctuation to achieve the condition where there is substantially no boundary layer between the solution and the growing metal particles at the one or more active zones of the cathode. Under this condition, transfer of dissolved metal atoms to the surface of the growing particle is not mass transfer controlled and the growth process is under kinetic control which provides a particle morphology suitable for fuel cell applications. In one embodiment, a turbulent flow is one where  $Re$  exceeds a transition value in the range of between about 1,000 and about 10,000. In a second embodiment, a turbulent flow is one where  $Re > \text{about } 1500$ .

Metal particle quality may also be enhanced by certain chemical additives in the electrolyte. For example, adding bismuth in the proportion 400 ppm  $Bi_2O_3$  to 40 liters of electrolyte, or adding indium in the proportion of 250 ppm  $In(OH)_3$  to 40 liters of electrolyte, was found to generally improve particle form and consistency.

Additionally, the force required to remove the particles from the active zones was tested. For zinc particle formation on Mg zones, it was determined that minimal force was required to dislodge the particles.

Metal particle shape and quality also depends on the construction of the cathode. For example, the morphology of the metal particles may be affected by the surface area of the active zones, and also by the spacing between active zones. To illustrate the formation of particles on active zones, Figure 14a shows a magnified cross sectional view of one embodiment of a cathode surface. Pins 1402 are shown protruding from

conductive substrate 1404, and insulated from each other at surface 1406 by insulating material 1408. A system operating as discussed above causes metal particles 1410 to form on active zones generally outwardly and upwardly, as shown.

A closer view of particle formation on the surface of an active zone is shown in  
5 Figures 14b and 14c. In the absence of the parametric constraints discussed above, and with active zones having large surface areas widely spaced from one another, zinc particle composition has been experimentally determined to result from three phases of growth. These experiments were conducted using cathodes having magnesium active zones approximately 0.5 mm in diameter. In the initial phase, metal deposits form as individual  
10 grains 1412 on the active zone 1414. The grains adhere weakly to the active zone, and tend to develop weak bonds between other grains. In the second phase, the metal deposits grow outwardly in the form of six to eight crystalline lobes 1416, forming a total diameter of about 0.6 to 0.8 mm. These lobes are anchored weakly to one or more grains previously deposited, and do not bond to other outwardly growing lobes. In the third  
15 phase, the lobes grow upwardly in the form of columns 1418 as shown in Figure 14a. The columns are generally not joined to each other, but bond weakly to the grain foundation, forming the general structure of particle 1410.

Metal particles that grow from grain foundations in this fashion are not suitable for use in anode beds of metal/air fuel cells. When these particles are generally subjected  
20 to mechanical scraping or anodic dissolution, the weak adhesive forces between the grains which make up the foundation of the particle are quickly broken, and the particle disintegrates into many small grains of about 200 microns in size, and into lobes of about 100 to 200 microns in diameter and 500 microns in length. In a fuel cell, these fine particles tend to accumulate in the flow channels or at the bottom of the anode bed. This  
25 leads to a reduction in electrolyte flow and premature cell failure.

In order to eliminate grain foundations from metal particles and promote the production of stronger particles, the surface area of the active zones and the spacing between active zones should be maintained within certain limits. To determine these limits, cathodes having different active zone geometries were configured to produce  
5 different batches of zinc particles. The particles were then sieved to remove particles smaller than 0.38 mm. The remaining particles were then subjected to a collision test by placing a 150 ml sample of the particles within a 45 wt % KOH solution and circulating the mixture through a hydraulic circuit consisting of a pump, a test cylinder, a ball valve, and conduit. After 4 hours of operation, the particles were collected and again sieved.  
10 The volume of particles smaller than 0.38 mm passing through the sieve were recorded as a percentage of the initial volume. The results showed that cathodes having active zones less than about 0.04 square mm spaced apart by less than about 2.0 mm (most preferably less than about 1.0 mm) produced zinc particles that were most resistant to disintegration. If circular, in one embodiment the diameter of the active zones should be less than about  
15 0.2 mm. In one example, the diameter is about 0.15 mm. These are high quality particles that tend to grow initially from lobes rather than from grains. In addition, the lobes of these particles tend to bond together, creating a metal particle that is coherent and mechanically strong, but also of low superficial density and high surface area. As a result, these particles have a high electrochemical reactivity, and are therefore most  
20 suitable for use in metal/air fuel cells and other industrial and chemical processes.

A skilled artisan will recognize from a reading of this disclosure that there are many ways to construct a cathode according to the invention that is within the preferred limits for active zone geometry. In one embodiment, illustrated in Figures 15a (top view) and 15b (side view), the cathode surface comprises a sliced planar cross section 1502 of  
25 an insulated bundle of wire conductors 1504. Wires 1506 having the proper diameter



may be held at the appropriate spacing by a special fixture 1508, and then surrounded by an insulating material 1510, for example, a thermoset epoxy compound. The bundle is then cured and sliced perpendicular to the axes of the wires to form wafers 1502 having the desired active zone geometry in cross section. A wafer may then be mechanically  
5 attached to a metal support plate by soldering, conductive adhesive, or other means, thereby electrically coupling the plate to the active zones 1512. Optionally, the assembly may then be coated with another layer of insulation so that the only exposed metal components are a bus connector and the active zones. The cathode surface having the active zones may be machined to create a smooth planar surface.

10 In another embodiment, the bundle may be produced by combining successively larger bundles of partially cured insulated wire. Multiple partially cured insulated wires, along with uncured insulator, are grouped together and pulled through a heat and pressure die to form a larger bundle with the proper cross sectional geometry. Multiple bundles can be combined in similar fashion with additional uncured insulator to form a single,  
15 larger bundle. The final bundle is cured and sliced into wafers as described above.

Figures 16a to 16c illustrate another embodiment of a method for constructing a cathode according to the invention. This method involves machining a metal plate 1602 to form a plurality of pins 1604 that protrude from the surface of plate 1602. Figure 16a shows a top view of one example of a plate 1602 machined to form pins 1604 in a  
20 generally square array, that is, a “pegboard” pattern of pins regularly spaced in rows at right angles to columns, where each pin is separated an equal distance from adjacent pins at its top, bottom, left and right. Figure 16b shows a side view of plate 1602. Figure 16c is a magnified side view of a portion of plate 1602, showing pins 1604 protruding above the surface of plate 1602, and separated by gaps 1606 machined between pins 1604. In  
25 one embodiment, plate 1602 is machined mechanically. In another embodiment, plate

1602 is machined by electric discharge machining. After machining pins 1604, plate 1602 is coated with a curable insulating material 1608, as shown in the magnified side view Figure 16d. After curing, insulating material 1608 and pins 1604 are further machined to form a smooth cathode surface 1610 having a plurality of active zones (the ends of pins 1604) separated by an insulator (cured and finished insulating material 1608). A magnified side view of the finished cathode surface 1610 is shown in Figure 16e. In a preferred embodiment, for the production of zinc particles, the pins are machined from magnesium plate in a generally hexagonal array, and coated with a commercial epoxy sealant to form the insulator. Zinc particles deposited on a generally circular cathode may be dislodged effectively by means of the rotary scraper described above.

Another embodiment of a method for constructing a cathode according to the invention involves coining a pattern of active zones onto a metal substrate, such as magnesium. In general, a plate comprising the substrate is stamped using a closed die set configured to impress the desired active zone geometry onto the surface of the plate. The cathode surface is then coated with an insulator and finished as described in previous embodiments. Figures 17a to 17g illustrate an alternative embodiment of the coining method in which individual coins 1702 having active zones 1704 are produced. In this embodiment, active zones 1704 are arranged in hexagonal array. Figure 17a illustrates a minimal number of active zones in hexagonal array, where the nearest active zones 1704 surrounding any particular active zone 1706 form a hexagonal pattern. That is, any single zone 1706 (except for zones on the perimeter of the array) is centrally spaced among six adjacent surrounding zones 1704 that are spaced equally from each other. This pattern is maintained as more zones are added to the array, as shown in Figure 17b.

As shown in Figure 17c, coins 1702 may generally comprise any geometric shape that can regularly divide a plane, for example, hexagonal, rectangular, or triangular shapes. Coins 1702 may be manufactured from metal stock in the form of strips 1708 having appropriate width (shown in Figure 17d) and thickness (shown in Figure 17e). For example, a strip 1708 may be prepared by covering one surface with a masking material 1710, and plating the opposite surface with a solderable or silver compatible metal 1712. After plating, masking material 1710 is removed, and coining blanks 1714 are punched out of the strip in a desired shape, as shown in Figure 17f. Each coining blank 1714 is then stamped with a pattern of active zones 1704, to produce a finished coin 1702, for example, the hexagonal coin depicted in Figure 17g. The plated sides of coins 1702 are then assembled to a conductive support plate 1716 by soldering or by means of a conductive bonding agent. When fully assembled, coins 1702 and comprise a planar cathode surface as depicted, for example, in Figure 17h.

Figure 18 illustrates another embodiment of a method for constructing a cathode according to the invention. In this method, an insulating area 1802 is chemically etched into the surface of a metal plate 1804 to define raised active zones 1806, as shown in Figure 18a. A layer of insulating film 1808 is then added between active zones 1806, as shown in a magnified side view in Figure 18b. In one embodiment, for the production of zinc particles, metal plate 1804 is composed of a magnesium alloy about 0.25 inch thick. By experimentation, this method yielded good results using magnesium alloy K1A having about 0.7% Zr. In another embodiment, active zones 1802 may be formed on an etched copper plate. The copper areas 1810 that form the active zones may then be plated with an additional layer of chromium 1812. Optionally, the copper may be plated first with a layer of nickel 1814, followed by a final layer of chromium 1812, as shown in Figure 18c.

A flowchart of an implementation of this method is illustrated in Figure 19. First, in step 1902, K1A Mg plates about 310 mm square by 3 mm thick are prepared by grinding flat to a tolerance of about 0.002 in. and polishing to an 8 micro inch finish. Next, in step 1904, one side of the plate is plated with tin by any conventional plating method. The side plated is the side intended for eventual attachment to a conductive backing plate. Next, in step 1906, the desired pin pattern is etched into the surface of the Mg plate by a conventional etching technique. The pattern advantageously defines the desired geometric spacing and surface area for the active zones. In step 1908, the etched pin pattern is laminated with a coating of insulating film. In the next step, 1910, a partially cured conductive epoxy or the like is laminated to the plated side of the Mg plate. This step may optionally include attachment of a protective sheet to the laminated layer of conductive epoxy. Then in step 1912, a planar cathode is formed from the plate by punching or machining to achieve a desired cathode shape. In step 1914, a hot platen press is used to laminate the cathode form to the support plate and to fully cure the epoxy. Next, in step 1916, a final coating of curable insulation is used to encapsulate the entire assembly. The insulator is cured in step 1918. Finally, step 1920 is performed to remove a portion of the cured insulation by machining, sanding, or polishing the cathode surface to expose the active zones and finish the assembly.

Another implementation of a method of manufacturing a cathode according to the invention comprises forming active zones on a metal substrate by deposition of titanium nitride by means of chemical vapor deposition. Titanium nitride is desirable for its low surface energy which discourages other materials from bonding to it. Metal particles forming on titanium nitride by electrodeposition are therefore easily removable by application of minimal force. The substrate may be composed of any metal suitable for the purpose, for example, copper, nickel, stainless steel, magnesium, or aluminum.

Active zones formed in this manner yield titanium nitride sites in the range of 0 to 1000 micrometers in height. In one embodiment, an insulating film of tantalum oxide, about 20 to 100 micrometers in height, is formed between the active zones and bonded to the substrate to complete the cathode surface.

5           A flowchart of an embodiment of a method of operation of a system for producing metal particles according to the invention is illustrated in Figure 20. In step 2002, a solution including dissolved metal is contained, for example, within a container as described in any of the above figures. Next, in step 2004, the temperature of the solution is maintained between 0 and about 100 degrees C. An anode as described above is at  
10   least partially immersed in the solution in step 2006. Similarly, in step 2008, a cathode configured with one or more active zones is at least partially immersed in the solution. The cathode may comprise any of the aforescribed, or similar, embodiments that is complimentary to the anode of step 2006.

          With the anode and cathode immersed in solution within the container, step 2010  
15   is performed to effect and maintain a turbulent flow of the solution past one or more active zones of the cathode. The velocity of the flow is at a level sufficient to avoid dendrite formation on the active zones. In one embodiment, the flow achieves a Reynolds number greater than about 1500. In another embodiment, the flow velocity is any velocity sufficient to produce turbulent flow that promotes good quality particle  
20   growth, i.e. non-brittle crystalline particles free of dendrite formations. In another embodiment wherein the solution comprises dissolved metal in electrolyte, the flow velocity is maintained between about 15 and about 20 gallons per minute.

          Next, in step 2012, an electric potential is applied across the anode and cathode sufficient to create a current density in the active zones greater than about 5 kA/m<sup>2</sup>. In

one embodiment, the current density is maintained in the range between about 10 kA/m<sup>2</sup> and 40 kA/m<sup>2</sup>. Through the foregoing steps, metal particles of a desired size are allowed to form on the active zones of the cathode in step 2014. In one embodiment, this step occurs by predetermining a time period which is sufficient to allow particles of a desired  
5 size to form in a particle production system according to the invention, loading the predetermined time period into a timer, and then operating a metal production system according to the invention until a time out condition is detected, at which point, particle growth is ceased.

In another embodiment of a method according to the invention, step 2002 may  
10 further comprise containing a solution having a molarity sufficient to promote good quality particle formation. For zinc particle formation from potassium zincate solution, the molarity should be in the range of about 0.1 M to about 4.5 M. In another embodiment, this step further comprises maintaining the molarity within the desired range during an entire operating cycle of the system.

15 Figure 21a is a flowchart of an embodiment of a method according to the invention for removing metal particles from the active zones of a cathode by scraping. In step 2102, it is determined when the particles have grown to a desired size. In one implementation, this can be accomplished visually, or by expiration of a time out condition as previously discussed. Next, step 2104 is performed. In step 2104, the  
20 scraper and cathode are relatively positioned so that the scraper effectively engages the surface of the cathode for purposes of particle removal. This step may be accomplished by positioning a cathode relative to a stationary scraper, by positioning a scraper relative to a stationary cathode, or both. Step 2106 then occurs. In step 2106, the particles are dislodged by relative motion between the scraper and the cathode surface.

Figure 21b is a flowchart of a second embodiment of a method according to the invention for removing particles from the cathode surface. This embodiment is applicable to a cathode in which the non-conductive material forms a perforated layer of insulation on the surface of the conductive material, and in which relative motion  
5 between the cathode conductive material and the conductive material is permitted. In step 2108, it is determined whether metal particles of a desired size have grown. Again, in one implementation, this step may occur through visual observation and through detection of a time out condition. Step 2108 is followed by step 2110. In step 2110, the particles are dislodged by relative motion between the conductive and non-conductive  
10 portions of the cathode surface.

Referring again to Figures 21a and 21b, other embodiments of a method according to the invention may further comprise additional steps for directing the particles dislodged in either step 2106 or 2110 into a collection area. One such embodiment comprises directing the particles by entraining them within a flow of the solution.  
15 Another embodiment comprises directing the dislodged particles by means of gravity. In either of these methods, the dislodged particles may then be collected or allowed to accumulate in a collection area, and eventually recovered for transport to a storage device or injected directly into a metal/air fuel cell thereby recharging the cell.

The various apparatus and methods presented throughout the foregoing discussion  
20 provide means for producing metal particles under controlled conditions. Operating systems such as those shown in Figures 1, 5 and 11 may yield high quality metal particles provided that parameters such as flow velocity, current density, temperature, and molarity are maintained within the preferred ranges. In addition, manufacturing tolerances for the cathode surface may be controlled to minimize variations in current densities in the active  
25 zones. Variations in the size of active zones of one cathode, which may range between

10 and 20%, can lead to substantial variations in the aggregate electrochemically active surface area of the one cathode as compared to other cathodes produced by the same manufacturing method. As a consequence, a power supply operating at a fixed output voltage, or otherwise configured to maintain current density within a preferred range for one cathode may be unable to maintain current density within the same range for another cathode. Thus, in order to counteract the effects of manufacturing variations among cathodes, additional system controls may be necessary for a system according to the invention to optimize its yield of high quality particles.

As an example, consider a 14.5 cm x 30 cm standard cathode having about 163,000 pins, which may be produced according to any of the above methods. Using a constant-current power supply, an optimal current density has been determined experimentally using the standard cathode in a system as described herein for zinc-particle production. Under conditions that maintain process parameters within the preferred ranges, the standard cathode will produce zinc particles of highest quality at a current density of about 34,340 A/m<sup>2</sup>. However, a second cathode manufactured by the same process and coupled to the same constant-current power supply may not produce particles of like quality if the second cathode has an electroactive area that varies substantially from the area of the standard cathode. For example, if the second cathode comprises an electroactive area 20% greater than standard, the current density will be accordingly reduced. As illustrated in the graph of Figure 13, low current densities can result in poorer particle quality, especially at high zincate concentrations where zinc deposits tend to form dendritic bridges between active zones. These dendrites cause the particles to fuse together, making the particles more difficult to remove from the cathode surface. Particles that remain fixed to the cathode surface continue to grow and eventually lead to system failure by short circuiting the cathode to the anode. If the short



cannot be removed by repeated action of the scraper, then the electrolyzer unit must be disassembled for cleaning.

The short-circuiting problem may be exacerbated by the presence of irregular areas on the active zones. This phenomenon is illustrated in Figure 22a, which is a magnified cross-sectional view of an electrolyzer 2200 showing cathode surface 2206 separated a distance G from anode 2216. Cathode surface 2206 comprises active zones 2202 on pins 2204 separated by insulator 2208. Active zones 2202 may contain one or more irregular areas 2240 comprising tiny cracks or notches that penetrate a pin 2204. Areas 2240 may occur during the normal course of manufacturing due to physical stresses on pins 2204. During electrolysis, areas 2240 provide anchoring points for metal particles 2210 growing on active zones 2202. When particles 2210 are removed from surface 2206 by scraping, a small amount of metal from a pin 2204 may be torn away from the site of an area 2240. After repeated cycles of electrodeposition and scraping, areas 2240 enlarge, allowing subsequently deposited particles 2210 to become further embedded within active zones 2202. Eventually, active zones 2202 become so damaged that embedded particles can no longer be removed by scraping. These particles become larger with each growth cycle and eventually short circuit cathode 2206 to anode 2216, thereby rendering the electrolyzer inoperable.

A cathode having an overabundance of irregular areas 2240 may be mechanically reconditioned to remove the outermost layer of the cathode surface and thereby extend the service life of the electrolyzer. Figure 22b shows a magnified cross-sectional view of a cathode surface 2206(b) of electrolyzer 2200 after reconditioning. Reconditioning a cathode surface such as 2206 may comprise grinding, sanding, buffing, polishing, or other suitable means, until a sufficient layer of material has been removed to produce a surface substantially free of irregular areas. In the example of Figure 22b, cathode surface 2206

has been reconditioned to remove an outer layer of thickness  $d$  to produce a smooth surface 2206(b) comprising pins 2204(b) separated by insulator 2208(b). Removal of cathode material of a thickness  $d$  on the order of about .01 mm to .001 mm should adequately recondition the cathode. Reconditioning may be accomplished using an accessory attachable to the particle scraping means. In other cases, reconditioning may require disassembly of the electrolyzer and removal of the cathode. The cathode may then be reconditioned by a separate process before reassembly into the electrolyzer.

Figure 23 illustrates a method 2300 of the present invention for operating of a metal particle electrolyzer to reduce the probability of short circuit failure. Method 2300 provides a consistent current density through the electrolyzer by monitoring the cell voltage developed across the anode and cathode when the electrolyzer is energized. In the first step 2302, an operating range for the cell voltage of an electrolyzer is determined. This range may be determined empirically for a particular electrolyzer design. For example, an optimal cell voltage may be selected based on operating experience, and an operating range selected to be within 20% of the optimal value. Alternatively, an operating range may be calculated as a function of the preferred range of current density. In step 2304, electrical current is supplied to the electrolyzer by means of a power supply, and the process of particle production commences, as previously described. Ideally, energizing the electrolyzer in this fashion will produce a cell voltage within or near the operating range that was determined in the previous step. In step 2306, the cell voltage is monitored. This may be accomplished, for example, by connecting low-resistance test leads to test points 2250 and 2260 of Figure 22a to measure the potential difference between anode surface 2216 and a conductive section of cathode surface 2206. Referring again to Figure 23, step 2308 is performed. In step 2308, current output from the power supply is adjusted responsive to the monitored cell voltage, as necessary to maintain the

cell voltage within the operating range. This step may be achieved by configuring the power supply as a voltage-controlled current source by a variety of techniques well known in the art. After performing step 2308, method 2300 loops back to step 2304 and may continue as desired.

5           Figure 24 illustrates a method 2400 according to the invention for operating a metal particle electrolyzer to reduce the probability of short circuit failure, and to extend the service life of the electrolyzer. Method 2400 extends electrolyzer service life by dissolving metal particles that become embedded on the cathode surface before the commencement of another growth cycle. The initial step 2402 comprises immersing an  
10 electrolyzer into a solution that includes dissolved metal. As described herein in previous embodiments, the electrolyzer comprises anode and cathode surfaces, and is configured to produce metal particles through electrolysis. In the next step 2404, a DC voltage is applied to the electrolyzer, the electrolysis process begins, and metal particles begin to form on the cathode surface. During this step, some of the particles may become  
15 embedded within irregularities in the cathode surface. In the next step 2406, when the particles achieve a desired size, particles that are not embedded are removed from the cathode surface by any of the removing means previously disclosed. The embedded particles are removed in the next two steps. First, in step 2408, the DC voltage being applied to the electrolyzer is reduced to a value, less than about 1.65 volts, that will  
20 preclude oxygen from evolving on the active zones. In an embodiment where the electrolyzer produces zinc particles from an electrolyte containing zincate ions according to equation (3), the DC voltage may be reduced in step 2408 to about 1.0 volt. Next, in step 2410, the polarity of the applied voltage is reversed, such that the electrode that was formerly the cathode achieves a higher electrical potential than the electrode that was  
25 formerly the anode. Reversing the polarity causes zinc particles that are embedded in the

active zones to dissolve into positively charged zinc ions which migrate toward, and eventually plate to, the negatively charged electrode that was formerly the anode. Reverse polarity is maintained for a time period of about 60 to about 300 seconds, or until embedded particles are substantially dissolved. After performing step 2410, method 2400  
5 loops back to step 2404 and another growth cycle may begin. Thus, during each growth cycle, method 2400 dissolves particles that become embedded in the active zones, thereby preventing excessive particle formation that may cause premature failure of the electrolyzer.

Another embodiment of the invention for operating an electrolyzer is illustrated in  
10 the flow chart of Figure 25. Method 2500 begins with step 2502, which comprises immersing a metal particle electrolyzer within a body of electrolyte solution that includes a dissolved metal. For example, the electrolyte may comprise a KOH solution including zincate ions and dissolved ZnO. Next, in step 2506, electric current is supplied to the electrolyzer using a power supply configured as in embodiments previously discussed.  
15 The flow of current through the electrolyzer creates a voltage potential across the electrolyzer cell. Preferably, the initial power supplied to the electrolyzer is accurately estimated to create a cell voltage within a predetermined range that is consistent with a preferred value for current density through the electrolyzer cathode. Next, in step 2506, the cell voltage is monitored across the electrolyzer anode and cathode, and fed back to  
20 the power supply. In step 2508, the current output of the power supply is adjusted responsive to the monitored voltage to maintain the cell voltage within the predetermined range. In the next step 2510, metal particles are removed from the cathode surface after the particles have achieved a desired size. Particle removal may be accomplished by scraping, or by any other suitable method. After particles are removed, step 2512 is  
25 performed, wherein the cell voltage is reduced to a value below a standard cell potential.

Next, in step 2514, the polarity of the cell voltage is reversed a first time. Reversing the polarity causes metal particles embedded within irregular areas of the active zones to dissolve and plate out on the surface of the electrode that was formerly the anode. Reverse polarity is maintained for a time period until embedded particles are substantially dissolved from the active zones. In step 2516, during application of reverse polarity voltage, peak current through the electrolyzer is monitored. As the size and number of irregular areas in the cathode surface increase, the volume of particles embedded within the surface will also increase, thereby reducing the initial electrical resistance to reverse-polarity current flow. The value of peak current is therefore an indication of the condition of the cathode surface. The measured value of peak current is then compared to empirical data in decision block 2518. If the peak current exceeds a selected operating limit (i.e. a predetermined value of current based on empirical data) that indicates excessive build-up of embedded particles, the method proceeds to step 2520. In step 2520, power to the electrolyzer is shut off, and in step 2522, the electrolyzer cathode is mechanically reconditioned. If in decision block 2518, the peak current does not exceed the operating limit, the method loops back to step 2504, the polarity is reversed a second time to restore the original polarity, and another growth cycle begins.

From the foregoing, it will be seen that embodiments of the invention are possible in which particles are produced having a size that is related to the size of the surface area of the active zones of a cathode. This factor in turn promotes consistent production of particles within a predetermined size range. In addition, embodiments are possible in which 1) the particles which are produced can be used directly in a metal/air fuel cell without first having to sort the particles by size; 2) seed particles are not required to initiate particle growth; 3) operation thereof occurs at high current densities, thereby enabling construction of a compact, efficient device with a high rate of particle output; 4)

operation thereof occurs at high current density and high liquid flow rate, thereby producing high quality crystalline metal particles over a wide range of reaction solution/dissolved metal concentrations; or 5) the metal particles that are produced are coherent and mechanically strong but also of low density and high surface area and  
5 therefore of high electrochemical reactivity.

Skilled artisans will appreciate that the aforescribed method is not limited to the recovery of zinc from alkaline solution. By appropriately adjusting the various process parameters, the method may be exploited for the recovery of other metals, for example, magnesium, aluminum, calcium, nickel, copper, cadmium, tin, or lead dissolved in a  
10 suitable electrolytic solvent.

While various embodiments of the invention have been described, it will be apparent to those of ordinary skill in the art that many more embodiments and implementations are possible that are within the scope of this invention. Accordingly, the invention is not to be restricted except in light of the attached claims and their  
15 equivalents.